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Aerodynamic parameters and sensible heat flux estimates for a semi-arid ecosystem

John H. Prueger[a,*], William P. Kustas[b], Lawrence E. Hipps[c], Jerry L. Hatfield[a]

[a] *USDA-ARS National Soil Tilth Laboratory, 2150 Pammel Drive, Ames, IA, USA*
[b] *USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD, USA*
[c] *Plant, Soils and Biometeorology, Utah State University, Logan, UT, USA*

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Abstract

Aerodynamic parameters of roughness length (z_0) and displacement height (d_0) for semi-arid grassland, mixed grass–mesquite and mesquite rangeland were computed from eddy covariance measurements of sensible heat flux (H), standard deviations of vertical velocity and air temperature (σ_w and σ_T), and mean wind speed (u) within the framework of Monin–Obukhov similarity theory. Reasonable estimates of z_0 were obtained for all sites but unrealistic d_0 values resulted for most sites except mesquite. Independent estimates of z_0 and d_0 were also determined at the mesquite site with a traditional wind speed profile method and compared with results computed from an approach using laser altimeter data. Results showed good agreement among approaches. Also, within the framework of flux–variance using, σ_T, and derived z_0, d_0 with u, computed H fluxes were evaluated and compared to eddy covariance measurements.

Keywords: Aerodynamic roughness length; Displacement height; Friction velocity; Eddy covariance; Mesquite dune

1. Introduction

The energy and water balances of native surfaces are strongly coupled to hydrology and climate as well as other biological and physical processes related to

*Corresponding author. Tel.: +1-515-294-7694; fax: +1-515-294-8125.
E-mail address: prueger@nstl.gov (J.H. Prueger).

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ecosystem structure and function. Heat, water and momentum exchange at a surface are turbulent processes often estimated from vertical gradients of temperature, water vapor and wind speed above the surface using flux–gradient relationships. These processes are non-linear and are related to soil moisture conditions, canopy structure, vegetated land cover distribution, topography (micro- and meso-scale) and surface albedos (Campbell and Norman, 1998).

With a flux–gradient approach, surface roughness and heterogeneity are typically characterized by two aerodynamic parameters, aerodynamic roughness length, z_0, and zero-plane displacement height (d_0). Aerodynamic roughness length relates to the efficiency of momentum exchange at the surface and d_0 represents the effective height of momentum absorption within the roughness elements (Campbell and Norman, 1998). Both z_0 and d_0 are important in aerodynamic formulations for modeling energy exchange processes across the soil–vegetation–atmosphere continuum. This is especially the case for models developed to estimate turbulent exchange processes for sparsely vegetated heterogeneous surfaces in semi-arid landscapes (Shuttleworth and Wallace, 1985).

Vegetation height, structure, density and landscape topography affect roughness parameters (Brutsaert, 1982). Estimating z_0 and d_0 is difficult but especially so for landscapes comprised of sparse or patchy vegetation typical of arid and semi-arid regions. Compared to agricultural crops, few studies have evaluated z_0 and d_0 for native desert grass and shrub communities (Wieringa, 1993). Some studies have evaluated aerodynamic parameters using wind profile approaches and flux–variance relations for desert environments (Weaver, 1990; Kustas et al., 1994).

The traditional logarithmic wind profile approach uses multiple levels of wind speed measurements to mathematically solve for z_0 and d_0 by minimizing the sum of square errors for wind speed and measurement height (Robinson, 1962; Stearns, 1970). Haenel (1993) proposed an iterative approach following Robinson (1962) to account for non-neutral conditions, and thus can use all data for the range of stabilities found during the course of a diurnal cycle. However, the approach is not likely to be applicable to heterogeneous surfaces where profiles of mean wind speed and scalars do not appear to follow Monin–Obukhov similarity thus violating important underlying assumptions of the wind profile method (e.g., Chen and Schwerdtfeger, 1989; Tsvang et al., 1998). Possible reasons can include; (1) surface heterogeneity effects producing a weakly developed equilibrated boundary-layer above a surface; (2) tower height limitations and the depth of a fully adjusted boundary-layer (FAL) over a surface can be such that measurements believed to be made in the FAL are in actuality made in the roughness sub-layer and thus subject to significant errors; (3) non-uniformity of vertical sources and sinks of heat and water vapor within sparse canopies are poorly defined as a single layer. For example, Kustas et al. (1998); Hipps and Kustas (2001) reported significant departures of observed temperature profiles for a coppice dune site under unstable conditions from those defined by Monin–Obukhov similarity theory. This may have resulted from large spatial variations of surface temperatures between dune and inter-dune spaces producing considerable scatter in the universal stability functions (e.g., Tsvang et al., 1998). In semi-arid landscapes, potential logistical and theoretical limitations inherent to wind profile techniques necessitates alternative approaches for estimating aerodynamic roughness parameters.

One such approach described by Weaver (1990) makes use of flux–variance relationships using eddy covariance measurements of scalar fluxes and turbulence statistics. However, Weaver (1990) only describes estimating one of the two aerodynamic roughness parameters, namely z_0 and does not explicitly evaluate the role of d_0 in the flux–variance equations. For most landscapes, the impact of the roughness elements (vegetation and topography) on momentum transport should include the effect of both aerodynamic roughness parameters in Monin–Obukhov similarity relations (Brutsaert, 1982).

In this paper, we evaluate a flux–variance approach using eddy covariance measurements of H, mean wind speed (u), the standard deviation of vertical wind speed and air temperature (σ_W, σ_T), to estimate aerodynamic roughness parameters (z_0, and d_0) and H using turbulent statistics for a semi-arid grassland, a transitional site containing a mixture of grasses and shrubs and a honey mesquite coppice dune site in a Northern Chihuahuan desert.

2. Theory

Using Monin–Obukhov similarity theory in the surface layer (10's of meters above a surface) the wind profile (i.e. traditional wind profile approach) is commonly assumed to be logarithmic (Brutsaert, 1982) and is expressed as

$$\bar{u} = \frac{u_*}{k} \ln\left[\frac{z - d_0}{z_0}\right] - \psi_m(\zeta), \tag{1}$$

where $\bar{u}$ is mean wind speed (m s^{-1}), $u_*(\tau/\rho)^{1/2}$ (m s^{-1}) friction velocity, τ surface shear stress (kg m^{-1} s^{-2}), ρ density of air (kg m^{-3}), k von Karman's constant (0.4, dimension less), z measurement height above a surface (m), z_0 roughness length (m) and d_0 the zero-displacement height (m), $\Psi_m(\zeta)$ is a stability function that accounts for buoyancy effects on the wind profile (for a review, see Högström, 1988, 1996) where $\zeta = z - d_0 / L$ and L is the Monin–Obukhov length (m) (Monin and Obukhov, 1954), that defines the surface boundary layer stability in terms of turbulent fluxes of heat and water as

$$L = -\frac{u_*^3 \rho}{kg[(H/T_A C_P) + +0.61E]}, \tag{2}$$

where g is acceleration due to gravity, (m s^{-2}), H, sensible heat flux (W m^{-2}), T_A, air temperature (K), C_p specific heat of air (J kg^{-1} K^{-1}), E is the rate of surface evaporation (kg m^{-2} s^{-1}) and all other terms have been previously defined.

Flux–variance relations were derived from Monin–Obukhov similarity theory to estimate momentum and sensible heat fluxes (Tillman, 1972) and have been used for water vapor and other scalar fluxes (Wesley, 1988). Further refinements to the technique have been developed (e.g., De Bruin et al., 1993). Early investigations indicated the approach does not work as reliably for latent heat flux (evaporation) relative to sensible heat flux when applied over heterogeneous surfaces, particularly sparse canopy-covered landscapes typical of arid and semi-arid landscapes (Weaver, 1990). In addition, some studies indicate that the "universal" constants for the flux–variance formulations of sensible heat flux varies with surface type and condition (De Bruin et al., 1991; Weaver, 1990; Padro, 1993).

Under moderately unstable conditions ($z - d_0/L < 0$), the equation relating H to temperature variance (σ_T) has the following form (Tillman, 1972):

$$H = \rho C_P u_* \left(\frac{\sigma_T}{C_1}\right)\left[C_2 - \frac{z - d_0}{L}\right]^{1/3}, \tag{3}$$

where C_1, C_2 are "universal" dimensionless constants derived experimentally and all other terms have been previously defined. For strongly unstable condition typically found in arid and semi-arid environment (i.e., free convective case where $z - d_0/L \ll 0$ and $u_* \to 0$) Eq. (3) is expressed:

$$H = \rho C_P \left[\left(\frac{\sigma_T}{C_1}\right)^3 \frac{kg(z - d_0)}{T_A}\right]^{1/2}, \tag{4}$$

where all terms have been previously defined. Using Monin–Obukhov similarity theory, a relationship is also derived for unstable conditions relating the variance of vertical wind velocity (σ_w) to the friction velocity u_* (Panofsky and Dutton, 1984):

$$u_* = \frac{\sigma_W}{C_3(1 - C_4(z - d_0)/L)^{1/3}}. \tag{5}$$

As in previous similar expressions, the universal constants C_3 and C_4 are dimensionless and are derived experimentally.

The magnitude of C_1 is found in the literature to range from approximately 0.9 (Padro, 1993) to 1.25 (Wesley, 1988) with a generally accepted literature value of 0.95 (Wyngaard et al., 1971). For heterogeneous surfaces, the values of C_2, C_3 and C_4 have been reported to be $\sim$ 0.04, 1.25, and 3 respectively (De Bruin et al., 1993).

Using the above set of equations and eddy covariance measurements of H and σ_w, previous studies have reported aerodynamic roughness parameters of z_0 and d_0 for similar semi-arid rangeland environments (Weaver, 1990; Kustas et al., 1994). However, mesquite dune landscapes have not been addressed. The procedure for estimating z_0 and d_0 is summarized as follows; initial values of z_0 and d_0 are selected from the literature (De Bruin et al., 1993), an iterative loop is conducted where L is computed from Eq. (2) using EC measurements of H, and λE (H_M, and λE_M, where λ is the latent heat of vaporization $\sim 2.45 \times 10^6\,\mathrm{J\,kg^{-1}}$ and subscript M signifies measured) and u_* is computed from the EC measurement of σ_w and Eq. (5) (u_{*V}); a solution is defined when there is negligible change in the magnitude of L and u_*. Computed sensible heat flux H can now be estimated from Eq. (3) (H_V), and u_* from Eq. (1) (u_{*U}), which contains the initial estimate of z_0. The appropriate values of z_0 and d_0 are found when the ratios of H_V/H_M and u_{*V}/u_{*U} approach unity.

3. Materials and methods

3.1. Site description

The Jornada Experimental Range (JER) is approximately 35 km northeast of Las Cruces, New Mexico on the Jornada del Muerto Plain of the Chihuahuan Desert. This is the largest desert (453,250 km^2/175,000 mi^2) in North America and is mostly located in Mexico and stretches into parts of the southwest United States. The JER was established in 1912 by the United States Department of Agriculture (USDA) and is part of the Agricultural Research Service (ARS) and the long-term Ecological Research (LTER) Program administered by the National Science Foundation (NSF).

The Jornada LTER site is primarily a semi-arid grassland (black grama) encompassing approximately 78,000 ha. The climate is characteristic of the northern region of the Chihuahuan desert and is the most arid of the North American grasslands. These grasslands are fragile dynamic systems and are sensitive to natural and anthropogenic influences. An example can be observed in the northern extent of the Chihuahuan desert where grass communities dominated by black grama (*Bouteloua eriopoda* (Torr.) Torr.) have experienced a gradual encroachment by honey mesquite (*Prosopis glandulosa* Torr.) shrubs in a process initiated by drought and aggravated by overgrazing practices during the last century (Buffington and Herbel, 1965; Gibbens et al., 1992). Increased landscape roughness from dune formation as well as a change in vegetation type (grasses to shrubs) likely alter the wind flow characteristics near the surface and may increase surface roughness and affect turbulent exchange with the lower boundary-layer of the atmosphere. Three sites were selected for intensive studies as part of the JORNEX project (Ritchie et al., 1998; Rango et al., 1998). The sites represented grass, shrub (honey mesquite), and a grass–shrub transition zone. Black grama was the dominant species for the grass site (referred to as grass-1) and was located within an exclosure to prevent animal grazing. Honey mesquite on coppice dunes represented the shrub site (referred to as mesquite site). The dunes vary in height from 0.75 to 2.5 m with honey mesquite growing on the tops of each dune. The transition site was comprised of a mix of vegetation components from both grass and mesquite sites with dunes in the initial stages of development not exceeding 0.5 m in height. During one of the field campaigns (September, 1996) two additional sites, one containing grass which was grazed (referred to as grass-2) and another with a variety of shrub species but no dune formation (referred to as shrub site) were also instrumented for surface energy flux measurements.

3.2. Vegetation measurements

Measurements of vegetation composition (species), cover, and height (h) were made along 150-m transects established at each JORNEX site using vertical line intercept techniques (Canfield, 1941; Eberhart, 1978). Permanent markers were geopositioned so that the same transects were measured during each campaign.

Along each transect three 30-m segments were measured for vertical line intercepts at 10-cm intervals for a total of 900 points per transect. Height measurements (nearest cm) of live plant material and standing litter were recorded by species. Since vegetated coppice dunes had substantially more relative relief, cross-sectional 100-m engineering survey results were combined with laser altimeter data to obtain an mean estimate of dune topography and mesquite vegetation height. Leaf area index (*LAI*) measurements were made along each transect with a non-destructive optical *LAI* sensor. *LAI* values were 1, 0.4 and 0.5 for the grass-1, mesquite and transition sites respectively. *LAI* measurements were not available for the grass-2 and shrub sites. For more detailed information on vegetation measurements see Havstad et al. (2000).

The vegetation measurements made at the three main sites (i.e., grass-1, mesquite and transition site) including the engineering transect for the mesquite site provided an estimate of mean vegetation/obstacle heights. For the mesquite site, dune heights ranged from 0.3 to 2 m with an average dune height of 0.85 m. The mesquite is clumped on the tops of the dunes, and when the vegetation height is added to the dune height, the range was from 1.1 to 3.5 m with an average total dune plus mesquite height of 1.8 m. The grass-1 site had a mean canopy height of 0.1 m while the mean canopy height at the transition site was 0.4 m. The grass-2 and shrub site average canopy heights were estimated to be approximately 0.1 and 0.5 m respectively.

3.3. Surface energy balance measurements

During intensive field campaigns sensible and latent heat fluxes (H and LE) were measured using eddy covariance (EC) at all sites. Measurements were made with one-dimensional (1-D) sonic anemometers (with a fine wire thermocouple) and krypton hygrometers. In addition the EC instruments provided measurements of the variances of vertical wind speed, σ_w, and air temperature, σ_T (Tanner et al., 1985; Tanner, 1988). The EC instruments were deployed 2 m above the local terrain at all sites except the mesquite site where sensors were mounted 3 m above the highest mesquite vegetation on a 10 m tower. Measurements of net radiation, Rn, air temperature, relative humidity, wind speed and direction were made the same heights as the EC measurements. Soil heat flux, G, was measured at each site using heat flux plates placed 0.08 m below the soil surface. Heat storage in the soil layer above the heat flux plates was computed using soil temperatures measured with thermocouples at depths of 0.02 and 0.06 m below the surface (and above the soil heat flux plate) and gravimetric estimates of soil water content and thermal conductivity (Hanks and Ashcroft, 1980). In addition, the 10-m tower erected at the mesquite dune site was also instrumented with cup anemometers and aspirated air temperature sensors at 3, 4, 5, 6, 8, and 10 m above the mesquite vegetation. Wind speed and temperature profile data were used to compute stability corrections ($\Psi_m(\zeta)$) to the profile data (Högström, 1988, 1996) and aerodynamic roughness parameters using the traditional wind profile iterative least square errors technique (Robinson, 1962; Kustas et al., 1989; Hatfield, 1989). For additional profile measurement details, see De Vries et al. (2001).

The EC measurements were scanned at 10 Hz with intermediate calculations of the variances and covariances computed every 10 min and averaged as 30-min output of H, λE, σ_w and σ_T. All other measurements were scanned at 10 s and output as 30-min averages. Preliminary analysis of the EC data from the grass-1 and mesquite sites are described by Prueger et al. (1998).

4. Results

4.1. Estimating d_0 and z_0

Initial values of the dimensionless constants C_1, C_2, C_3, C_4 selected for the flux–variance procedure are provided in Table 1 from De Bruin et al. (1993). In this study we confined our analysis to the unstable-free convective condition range, only data with measured sensible heat flux $(H_M) > 50\,\mathrm{W\,m^{-2}}$ were selected and used for estimating the roughness parameters. Canopy/obstacle heights, h, from the vegetation measurements and engineering surveys, and estimates of d_0 and z_0 using the procedure described above are presented in Table 2. The magnitudes of z_0 were similar to literature values reported for native grass and shrub land ecosystems in semi-arid regions (Weaver, 1990). However, the magnitude of d_0 for three of the five sites was larger than the estimated mean vegetation height (Table 2). This is not a physically plausible solution particularly for the grassland sites where there were no additional complicating effects such as terrain and local discontinuities in vegetation cover (Kustas et al., 1994).

A sensitivity analysis of the set of equations used to compute the roughness parameters was conducted. The results suggest a sensitive inverse relationship between the magnitude of C_1 and value of d_0, while all other constants (i.e., C_2 through C_4) have a relatively minor impact on the estimation of d_0. If C_1 was increased by 5% (0.95–1.0) the effect on predicted d_0 was a reduction by nearly 40% while changes in z_0 were relatively minor (Table 3). By changing C_1, d_0 results in general were more realistic, but not for the grass sites where d_0 values remained greater than the height of the grass. The value of C_1 was further increased to $C_1 = 1.1$, which is approximately midway between its observed range and the value used by Kustas et al. (1994) for semi-arid rangelands. This again resulted in relatively minor changes to z_0 at all sites but physically unrealistic values for d_0 ($d_0 < 0$) at four of the five sites.

Table 1
Values for the constants used in the variance formulations

Constant	Value
C_1	0.95
C_2	0.04
C_3	1.25
C_4	3

Table 2
Estimates of d_0 and z_0 using variance technique with values of constants defined in Table 1

Site	h (m)	d_0 (m)	z_0 (m)
Grass-1	0.1	0.8	0.015
Grass-2	0.1	0.5	0.013
Transition	0.45	0.25	0.028
Shrub	0.5	0.55	0.027
Mesquite	1.5	0.9	0.043

Mean canopy/obstacle heights, h, for each site are listed.

Table 3
Estimates of d_0 and z_0 using variance technique with $C_1 = 1$ and values of other constants defined in Table 1

Site	h (m)	d_0 (m)	z_0 (m)
Grass-1	0.1	0.6	0.012
Grass-2	0.1	0.3	0.011
Transition	0.45	0	0.026
Shrub	0.5	0.3	0.025
Mesquite	1.5	0.5	0.038

Mean canopy/obstacle heights, h, for each site are listed.

As mentioned earlier, other studies using the variance approach for predicting scalar fluxes indicate that C_1 may vary with surface type or land use (e.g., Padro, 1993). Lloyd et al. (1991) reported that the variation in C_1 is significantly affected by the magnitude of d_0 used in Eq. (3) or (5), particularly if the measurement height z is near the vegetation canopy. Another approach for computing d_0 described in De Bruin and Verhoef (1997) was also attempted, but in many cases the resulting $d_0 < 0$, another physically unrealistic solution. This occurred even when selecting data to meet criteria that would most likely satisfy the free convective limit, namely when $H_M > 150\ \mathrm{W\,m^{-2}}$ and $u < 2\ \mathrm{m\,s^{-1}}$. The results of the present study also suggest that the variance approach cannot be used to recover reasonable values for d_0.

Since physically realistic d_0 values could not be obtained by the above set of equations, an alternative simple analytic expression from Raupach (1994, 1995) was employed to independently estimate d_0 from the vegetation height (h) and LAI. The form of this expression is

$$\frac{d_0}{h} = -1\left[\frac{1 - \mathrm{e}^{\left(-\sqrt{cd_1\Lambda}\right)}}{\sqrt{cd_1\Lambda}}\right], \tag{6}$$

where cd_1 is an empirical constant estimated from laboratory and field data to be on the order of 7.5 (Raupach, 1994) and Λ is the area index of the roughness elements that can be estimated from a leaf area index or a canopy area index. For this study we used the measured LAI as a surrogate for Λ. Using Eq. (6) resulted in more constrained probable expressions of $d_0 \sim 0.5h$, $d_0 \sim 0.7h$ for the grass and mesquite sites respectively. Once the value of d_0 was defined the value of C_1 and z_0 were computed again by iteration until both ratio's H_V/H_M and u_{*V}/u_{*U} approached unity. The resulting values of C_1 and z_0 are presented in Table 4. The values of C_1 all fall within the range observed in previous studies, but the magnitudes did not correlate with cover type. Both the shrub and grass-2 sites have similar C_1 values ≈ 1 while the transition and mesquite sites have $C_1 \approx 0.95$ and the grass-1 site has $C_I \approx 1.1$. There is little change in the original estimates of z_0 using $C_1 = 0.95$ for all sites (Table 2). This suggests that this approach can provide reasonable and robust estimates of z_0 when d_0 is determined independently.

Roughness parameters at the mesquite site were also estimated using the traditional wind profile technique. Wind profile data were selected for near-neutral conditions yielding nearly 300 observations. Aerodynamic roughness parameters computed from the wind profile technique and results reported by De Vries et al. (2001) who employed a remote sensing procedure using laser altimeter data (Menenti and Ritchie, 1994) for the same mesquite site were compared with results from the flux variance approach. Tables 5 and 6 present a comparison of the roughness parameters for three methods at the mesquite dune site. In Table 5 independent estimates of d_0 from the wind profile, laser altimeter and Raupach's expression compared well with the wind profile method resulting in the largest d_0 and the laser altimeter results the lowest. The combined average ratio of d_0/h for the three methods was 0.58. Table 6 show the results for z_0 from the wind profile, laser altimeter and flux–variance approaches. The wind profile resulted in the largest estimate for z_0 while the laser altimeter and flux–variance methods were identical. In general these

Table 4
Estimate of z_0 with a variable C_1 and fixed d_0 with values of the other constants defined in Table 1

Site	h (m)	C_1 (-)	d_0 (m)	z_0 (m)
Grass-1	0.1	1.11	0.05	0.01
Grass-2	0.1	1.04	0.05	0.01
Transition	0.45	0.96	0.2	0.028
Shrub	0.5	1.02	0.2	0.024
Mesquite	1.5	0.94	1	0.044

Mean canopy/obstacle heights, h, for each site are listed.

Table 5
Comparison of d_0 for the mesquite site using wind profile, laser altimeter and Raupach 1994 (see text for details)

Technique	d_0 (m)
Wind profile	1
Laser altimeter	0.7
Raupach	0.9

Table 6
Comparison of z_0 for the mesquite site using wind profile, laser altimeter and variance technique (see text for details)

Technique	z_0 (m)
Wind profile	0.07
Laser altimeter	0.04–0.05
Variance	0.04–0.05

results indicate good agreement among the different approaches for estimating aerodynamic roughness parameters for a mesquite dune surface in an semi-arid environment.

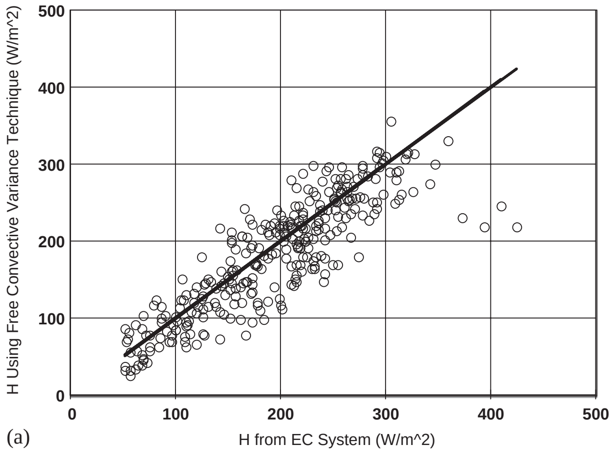
4.2. Estimating sensible heat fluxes

The use of second order turbulent statistics with the flux–variance technique for estimating sensible heat fluxes has been investigated (e.g., Katul et al., 1996). This represents an alternative to Bowen-ratio and eddy covariance techniques for estimating latent and sensible heat fluxes in semi-arid regions. Important advantages of the flux–variance approach are simplicity of measurements (time series measurements of air temperature T_A, 2–10 Hz) and inexpensive instrumentation (compared with EC). In addition, flux–variance methods appear not to be affected by position within the roughness sub-layer and measurements are not constrained by flow distortion or wind direction as are more traditional aerodynamic methods (Kustas et al., 1994; Katul et al., 1995).

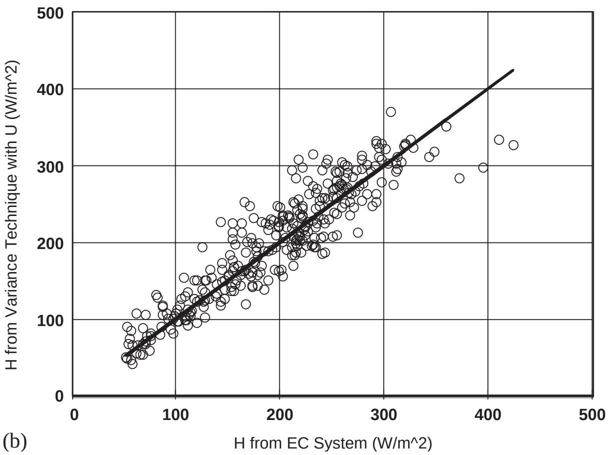
Using a global value for C_1 ($=1$), two estimates of H were computed. The first used the free convection assumption (Eq. (4)) and the second, the full expression which included the influence of mechanical transport (Eq. (3)). The u_* values were computed by iteration using the roughness parameters from Table 4 and wind speed observations with Eqs. (1) and (2). Note that neither approach use H_M when computing an estimate. Results are shown in Fig. 1(a) and (b). For the case that includes the effects of mechanical transport via Eqs. (1)–(3), estimates of H compared well with those from eddy covariance resulting in a root mean square error (RMSE) of 30 W m^{-2} and an $r^2 = 0.85$. For the free convective case, (Eq. (4)) Fig. 1(b) shows more scatter, higher RMSE 40 W m^{-2}, and an $r^2 = 0.74$. More variability was observed using Eq. (4) relative to Eq. (3). This suggests that effects of momentum transport need to be accounted for even under conditions approaching the free convective limit and should be included in sensible heat flux computations when possible.

5. Summary and conclusions

A method that combines sensible heat flux measurements from eddy covariance with flux–variance relationships was investigated to compute aerodynamic



(a)



(b)

Fig. 1. (a) H estimated using flux–variance technique for temperature under the free convective limit (i.e., Eq. (4)) versus eddy covariance measurements. Line is 1:1, (b) H estimated using flux–variance technique for temperature versus eddy covariance measurements with the influence of mechanical turbulence included (i.e., Eq. (3)) where u_* is estimated from Monin Obukhov similarity, Eqs. (1) and (2) (see text). Line is 1:1.

roughness parameters for a semi-arid rangeland. This is an operational technique for estimating H requiring only high frequency measurements of air temperature, wind speed observations, and reliable estimates of z_0 and d_0. The method computed reasonable values of roughness length (z_0) for all sites that were of a comparable magnitude with reported values of other semi-arid landscapes. Roughness length estimates at the mesquite dune site compared well with those computed independently from wind profile and remotely sensed laser altimeter data. Displacement height, d_0, results were mixed and were strongly dependent on the value of the constant C_1. For grass surfaces, unrealistic values of d_0 resulted.

However, the estimated mesquite d_0 values appear to be physically reasonable. An alternative approach was examined that also did not provide reliable d_0 estimates for this plant community. The estimates of z_0 were not strongly affected by the values of d_0.

The grass sites had $z_0 \sim 0.01$ m, the shrub and transition sites with slight topography had $z_0 \sim 0.025$ m, while the mesquite dune site resulted in $z_0 \sim 0.045$ m. However, the magnitude of C_1 was not strongly correlated to land cover type and thus cannot be estimated a priori. Estimates of sensible heat flux using the variance approach compared well (mean $r^2 = 0.80$) with eddy covariance measurements. Improved agreement was obtained by including contributions of mechanical transport in the formulation. Since roughness parameters are critical to modeling the surface energy and water balance of semi-arid landscapes, it is important to develop theoretically sound and robust methods for estimating roughness parameters for semi-arid landscapes.

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References

Brutsaert, W., 1982. Evaporation into the Atmosphere. Reidel, Holland, 299pp.

Buffington, L.C., Herbel, C.H., 1965. Vegetational changes on a semidesert grassland range from 1853 to 1963. Ecological Monographs 35, 139–164.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics. Springer-Verlag, New York.

Canfield, R.H., 1941. Application of the line intercept method in sampling range vegetation. Journal of Forestry 39, 388–394.

Chen, F., Schwerdtfeger, P., 1989. Flux–gradient relationships for momentum and heat over a rough natural surface. Quarterly Journal of the Royal Meteorological Society 115, 335–352.

De Bruin, H.A.R., Verhoef, A., 1997. A new method to determine the zero-plane displacement. Boundary -Layer Meteorology 82, 159–164.

De Bruin, H.A.R., Bink, N.I., Kroon, L.J.M., 1991. Fluxes in the surface layer under advective conditions. In: Schmugge, T.J., Andre, J.C. (Eds.), Workshop on Land Surface Evaporation Measurement and Parameterization. Springer, New York, pp. 157–169.

De Bruin, H.A.R., Kohsiek, W., Van Den Hurk, B.J.J.M., 1993. A verification of some methods to determine the fluxes of momentum, sensible heat and water vapor using standard deviation and structure parameter of scalar meteorological quantities. Boundary-Layer Meteorology 63, 231–257.

De Vries, A.C., Ritchie, J.C., Klaassen, W., Menenti, M., Kustas, W.P., Rango, A., Prueger, J.H., 2001. Effective aerodynamic roughness estimated from airborne laser altimeter measurements of surface features. International Journal of Remote Sensing, in press.

Eberhart, L.L., 1978. Transect methods of population studies. Journal of Wildlife Management 42, 1–31.
Gibbens, R.P., Beck, R.F., McNeely, R.P., Herbel, C.H., 1992. Recent rates of mesquite establishment in the northern Chihuahuan desert. Journal of Range Management 45, 585–588.
Haenel, H.-D., 1993. Surface-layer profile evaluation using generalization of Robinson's method for the determination of d and z_0. Boundary-Layer Meteorology 65, 55–67.
Hanks, R.J., Ashcroft, G.L., 1980. Applied Soil Physics (Advanced Series in Agricultural Sciences, Vol. 8); Springer, Berlin–Heidelberg, 159pp.
Hatfield, J.L., 1989. Aerodynamic properties of partial canopies. Agricultural and Forest Meteorology 46, 15–22.
Havstad, K.M., Kustas, W.P., Rango, A., Ritchie, J.C., Schmugge, T.J., 2000. Jornada experimental range: a unique arid land location to validate satellite systems. Remote Sensing of Environment 74, 13–25.
Hipps, L.E., Kustas, W.P., 2001. Patterns and organization in evaporation. In: Grayson, R., Bloschl, G. (Eds.), Spatial Patterns in Catchment Hydrology, Observation and Modeling. Cambridge University Press, Cambridge.
Högström, U., 1988. Non-dimensional wind and temperature profiles in the atmospheric surface layer: a re-evaluation. Boundary-Layer Meteorology 42, 55–78.
Högström, U., 1996. Review of some basic characteristics of the atmospheric surface layer. Boundary-Layer Meteorology 78, 215–246.
Katul, G., Goltz, S.M., Hsieh, C.-I., Cheng, Y., Mowry, F., Sigmon, J., 1995. Estimation of surface heat and momentum fluxes using the flux variance method above uniform and non-uniform terrain. Boundary-Layer Meteorology 74, 237–260.
Katul, G., Hsieh, C.-I., Oren, R., Ellsworth, D., Phillips, N., 1996. Latent and sensible heat flux predictions from a uniform pine forest using surface renewal and flux variance methods. Boundary-Layer Meteorology 80, 249–282.
Kustas, W.P., Choudhury, B.J., Kunkel, K.E., Gay, L.W., 1989. Estimate of the aerodynamic roughness parameters over an incomplete canopy cover of cotton. Agricultural and Forest Meteorology 46, 91–105.
Kustas, W.P., Blanford, J.H., Stannard, D.I., Daughtry, C.S.T., Nichols, W.D., Weltz, M.A., 1994. Local energy flux estimates for unstable conditions using variance data in semi-arid rangelands. Water Resources Research 30 (5), 1351–1361.
Kustas, W.P., Prueger, J.H., Hipps, L.E., Ramalingam, K., Hatfield, J.L., 1998. Application of Monin–Obukhov similarity over a mesquite dune site in the Jornada experimental range. AMS Proceedings of the 23rd Conference on Agricultural and Forest Meteorology, Albuquerque, NM, pp. 216–219.
Lloyd, C.R., Culf, A.D., Dolman, A.J., Gash, J.H., 1991. Estimates of sensible heat flux from observations of temperature fluctuations. Boundary-Layer Meteorology 57, 311–322.
Menenti, M., Ritchie, J.C., 1994. Estimation of effective aerodynamic roughness of Walnut Gulch watershed with laser altimeter measurements. Water Resources Research 30 (5), 1329–1337.
Monin, A.S., Obukhov, A.M., 1954. Basic laws of turbulent mixing in the ground layer of the atmosphere. Trudy Geofizicheskogo Instituta, Akademiya Nauk SSSR 151, 163–187.
Padro, J., 1993. An investigation of flux–variance methods and universal functions applied to three land-use types in unstable conditions. Boundary-Layer Meteorology 66, 413–425.
Panofsky, H., Dutton, J., 1984. Atmospheric Turbulence: Models and Methods for Engineering Applications. Wiley, New York, 397pp.
Prueger, J.H., Kustas, W.P., Hipps, L.E., Hatfield, J.L., Ramalingam, K., 1998. Surface energy partitioning over black grama and mesquite dune biomes in a northern Chihuahuan desert. AMS Proceedings, Special Symposium on Hydrology, Phoenix, AZ, pp. 216–219.
Rango, A., Ritchie, J.C., Kustas, W.P, Schmugge, T.J., Havstad, K.M., 1998. JORNEX: remote sensing to quantify long-term vegetation change and hydrological fluxes in an arid rangeland environment. In: Wheater, H., Kirby, C. (Eds.), Hydrology in a Changing Environment, Vol. 2. British Hydrology Society, Wiley, New York, pp. 585–590.
Raupach, M.R., 1994. Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. Boundary-Layer Meteorology 71, 211–216.

Raupach, M.R., 1995. Corrigenda. Boundary-Layer Meteorology 76, 303–304.

Ritchie, J.C., Rango, A., Kustas, W.P., Schmugge, T.J., Havstad, K.M., Everitt, J.H., Hipps, L.E., Ramalingam, K., 1998. JORNEX: a remote sensing campaign to study plant community response to hydrologic fluxes in desert grasslands. In: Potts, D.F. (Ed.), Rangeland Management and Water Resources. American Water Resources Society, Herndon, VA, pp. 65–74.

Robinson, S.M., 1962. Computing wind profile parameters. Journal of Atmospheric Science 19, 189.

Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse canopies—an energy combination theory. Quarterly Journal of the Royal Meteorological Society 111, 839–855.

Stearns, C.R., 1970. Determining surface roughness and displacement height. Boundary-Layer Meteorology 1, 102.

Tanner, B.D., 1988. Use requirements for Bowen-ratio and eddy correlation determination of evapotranspiration. In: DeLynn, R.H. (Ed.), Planning Now for Irrigation and Drainage in the 21st Century. Irrigation and Drainage Division of the ASCE, New York, pp. 605–616.

Tanner, B.D., Tanner, M.S., Dugas, W.A., Campbell, E.C., Bland, B.L., 1985. Evaluation of an operational eddy correlation system for evapotranspiration measurement. In: Advances in Evapotranspiration, Proceedings of the National Conference on Advances in Evapotranspiration. American Society of Agricultural Engineers, St. Joseph, MI, pp. 87–99.

Tillman, J.E., 1972. The indirect determination of stability, heat and momentum fluxes in the atmospheric boundary layer from simple scalar variables during dry unstable conditions. Journal of Applied Meteorology 11, 783–792.

Tsvang, L.R., Kukharts, V.P., Perepelkin, V.G., 1998. Atmospheric turbulence characteristics over a temperature-inhomogeneous land surface. Part II: the effect of small-scale inhomogeneities of surface temperature on some characteristics of the atmospheric surface layer. Boundary-Layer Meteorology 8, 103–124.

Weaver, H.L., 1990. Temperature and humidity flux–variance relations determined by one-dimensional eddy correlations. Boundary-Layer Meteorology 53, 77–91.

Wesley, M.I., 1988. Use of variance techniques to measure dry air–surface exchange rates. Boundary-Layer Meteorology 44, 13–31.

Wieringa, J., 1993. Representative roughness parameters for homogeneous terrain. Boundary-Layer Meteorology 63, 323–364.

Wyngaard, J.C., Cote, O.R., Izumi, Y., 1971. Local free convection, similarity and the budgets of shear stress and heat flux. Journal of Atmospheric Science 28, 1171–1182.